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Grid-connected photovoltaic power systems: Technical and potential problems—A review

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ABSTRACT

Traditional electric power systems are designed in large part to utilize large baseload power plants, with limited ability to rapidly ramp output or reduce output below a certain level. The increase in demand variability created by intermittent sources such as photovoltaic (PV) presents new challenges to increase system flexibility. This paper aims to investigate and emphasize the importance of the grid-connected PV system regarding the intermittent nature of renewable generation, and the characterization of PV generation with regard to grid code compliance. The investigation was conducted to critically review the literature on expected potential problems associated with high penetration levels and islanding prevention methods of grid tied PV. According to the survey, PV grid connection inverters have fairly good performance. They have high conversion efficiency and power factor exceeding 90% for wide operating range, while maintaining current harmonics THD less than 5%. Numerous large-scale projects are currently being commissioned, with more planned for the near future. Prices of both PV and balance of system components (BOS) are decreasing which will lead to further increase in use. The technical requirements from the utility power system side need to be satisfied to ensure the safety of the PV installer and the reliability of the utility grid. Identifying the technical requirements for grid interconnection and solving the interconnect problems such as islanding detection, harmonic distortion requirements and electromagnetic interference are therefore very important issues for widespread application of PV systems. The control circuit also provides sufficient control and protection functions like maximum power tracking, inverter current control and power factor control. Reliability, life span and maintenance needs should be certified through the long-term operation of PV system. Further reduction of cost, size and weight is required for more utilization of PV systems. Using PV inverters with a variable power factor at high penetration levels may increase the number of balanced conditions and subsequently increase the probability of islanding. It is strongly recommended that PV inverters should be operated at unity power factor.

Contents

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Nomenclature

C_T	empirical constant relating to the impact of cell temperature on output (dimensionless)
DF	diode factor, dimensionless e electric charge on an electron, 1.60×10^{-19} C
E_A	array output energy (kWh)
E_{PV}	energy to grid (kWh)
G_{STC}	reference irradiance at STC (1 kW/m^2)
h_c	convective heat transfer coefficient (W/(m^2 K))
h_r	radiative heat transfer coefficient (W/(m^2 K))
H_T	mean daily irradiance in array plane (kWh/m^2 d)
$H_{(t,\beta)}$	is the incident irradiance in the plane of the PV generator
I_L	light generated current (A)
I_o	diode current (A)
I_{sc}	short circuit current at reference values (A)
I_{mp}	current at maximum power point (A)
k	Boltzmann constant, 1.38×10^{-23} J/(K mol)
K_a	thermal conductivity of air (W/(m K))
L	distance from entry point (m)
m	number of parallel connected cells (dimensionless)
n	number of series connected cells (dimensionless)
N	number of panels in surface (dimensionless)
P	panel power output (W)
P_{mp}	is the dc power supplied by the PV generator when operating in the maxim power point
P_O	peak power (W_P)
P^0_{PV}	is the maximum power of the PV generator
Q	solar insolation (W/m^2)
Q_{ref}	reference insolation (usually 1000 W/m^2) (W/m^2)
T_c	temperature in the rear part of the cell or PV module (K)
T_{ref}	reference temperature (usually at 298 K) (K)
V_{mp}	voltage at maximum power point at reference values (V)
V_{mpp}	voltage at maximum power point (V)
V_{oc}	open circuit voltage at reference values (V)
η_e	electricity generating efficiency, dimensionless
λ_{mp}	is temperature coefficients of maximum power voltage of the PV modules
AFD	active frequency drift (frequency bias)
AFDPF	AFD with positive feedback (aka SFS)
BOS	balance of system components
DSP	digital signal processor
FCC	federal communications commission
GTO	gate turn off device
JFET	junction field-effect transistor
OFR	over frequency relay
PCS	power conditioning system (aka inverter)
PJD	phase jump detection
PLL	phase locked loop
POCC	point of common coupling
SFS	sandia frequency shift
SMS	slide-mode frequency shift
SOV	silicon oxide varistor, a transient surge suppression device
STC	standard test conditions
UFR	under frequency relay
UIPV	utility-interactive photovoltaic (system)

1. Introduction

Grid interconnection of PV power generation system has the advantage of more effective utilization of generated power. However, the technical requirements from both the utility power system grid side and the PV system side need to be satisfied to ensure the safety of the PV installer and the reliability of the utility grid. Clarifying the technical requirements for grid interconnection and solving the problems such as islanding detection, harmonic distortion requirements and electromagnetic interference are therefore very important issues for widespread application of PV systems [1]. Grid interconnection of PV systems is accomplished through the inverter, which convert dc power generated from PV modules to ac power used for ordinary power supply to electric equipments. Inverter system is therefore very important for grid-connected PV systems.

Grid connection and extension costs are significant factors for integrating renewable energy sources-electricity (RES-E) generation technologies into an existing electricity network. Prices of both PV and BOS are decreasing following a trend of increased production and improved technology. This explains the high amount of subsidies for R&D and application of PVs in industrialized countries. The solar PV electric power generation will play an important role in the future energy supply in China.

According to the present plan, total PV power installations will reach 350 MW by 2010, 1.8 GW by 2020 and 600 GW by 2050. According to forecasts made by the Chinese Electric Power Research Institute, renewable energy installations will account for 30% of the total electric power installations in China by 2050, of which PV installations will account for 5% [2].

In fact, growing of PV for electricity generation is one of the highest in the field of the renewable energies and this tendency is expected to continue in the next years [3]. As an obvious consequence, an increasing number of new PV components and devices, mainly arrays and inverters, are coming on to the PV market [4]. The energy production of a grid-connected PV system depends on various factors. Among these we distinguish the rated characteristics of the components of the PV system, the installation configuration, the geographical siting of the PV system, its surrounding objects, and defects that occur during its operation. The need for PV arrays and inverters to be characterized has then become a more and more important aspect [5–9]. Due to the variable nature of the operating conditions in PV systems, the complete characterization of these elements is quite a difficult issue.

The performance of grid-connected PV systems can be evaluated by investigating the performance ratio (PR) [10], which is defined by the ratio of the system efficiency and the nominal efficiency of PV modules under STC [11]. The average values of PR were found to be 66% for one hundred rooftop mounted PV in Germany [12–14], 55–70% for eight grid-connected PV systems in Europe [15], while it was 63–76% in the Netherlands [16]. These values apply to systems using solar cells made of poly- and mono-crystalline silicon.

From the performance analysis of 260 PV plants in the IEA-PVPS Task 2 database the annual performance ratios for the different types of systems [17], could be 0.6–0.8, 0.1–0.6 and 0.3–0.6 for grid-connected PV systems, stand-alone systems without back-up and stand-alone systems with back-up, respectively. The well maintained PV systems showed an average PR value of typically 0.72 at an availability of 98%. Despite good results, which have been obtained in many of the grid-connected systems, the investigation of the operational behavior of the reported PV systems has identified further potential for optimization.

It is often assumed, in the analysis of grid-connected generators, that the grid supply exhibits a perfect voltage waveform and that the embedded generators themselves are unaffected by perturbations of the grid, i.e. that any disturbance produced is due solely to the embedded sources. In reality, however, the operation of these power electronic generators, and hence the current waveform they source into the network, can be significantly affected by minor distortion of the voltage waveform at the point of connection [18].

With the proliferation of production and improved technologies, the system requires to be standardized, and thus ensuring, issues of safety and quality in manufacture, application, and use. Standards will serve to build consumer confidence, reduce costs and further expand PV development [19].

PV simulation tools are useful to (i) perform detailed analysis of system performance under real field operating conditions, (ii) investigate the impact of different load profiles, (iii) verify system sizing and determine the optimal size of PV components and (iv) assess the viability of a PV system in terms of energy production and life cycle cost of the system [20]. Various simulation tools are currently available to perform PV simulation and can be found in [21–29].

Empirical relationships have also been developed using real field test data for different types of PV cells to characterize different PV parameters to predict PV performance [30]. Different mathematical models have been developed for individual PV components to perform simulation of the overall PV system [31–33]. A scenario base PV software tool has been developed to determine the future progress of grid-connected PV systems [34]. Various long-term PV performance models have been developed to simplify the process of hour by hour simulation [35–39]. The developed models are useful to design optimal configurations of PV systems.

At present, the main PV-powered products include solar street, traffic signal, garden and lawn lamps, calculators and solar toys etc. China has become the largest producer of PV-powered products in the world. The annual usage of solar cells for these products has reached 20 MW_p and there is a great deal of exportation [2].

With so many additional functions being allocated to the inverter, the inverter becomes ever more critical to the system function, and the reliability of current technology inverters becomes a significant issue of concern. This investigation aims to emphasize the importance of the grid-connected PV system regarding the intermittent nature of renewable generation, and the characterization of PV generation with regard to grid code compliance. Also, will focus on the technical requirements for grid interconnection and solving the interconnect problems such as islanding detection, harmonic distortion requirements and electromagnetic interference.

2. Glossary of terms and acronyms

The field of power electronics abounds with unfamiliar and ambiguous terminology. The glossary in Table 1 provides definitions in general use in the PV industry as related to inverters and should help establish a common language for the different types of inverters and the power components used in them. Some functions such as the inverter control methods or ties to standards and codes are also defined here [40,41].

The current commercially available inverter hardware used for uninterruptible power supplies or for remote (short-term) power applications was found to be incompatible with the new requirements of a PV power system [42]. Costs were too high and efficiencies were too low. For stand-alone applications, the existing hardware had been designed to interface with small power tools or lighting loads [43]. Parameters such as voltage regulation, power quality, high overall efficiency, low tare losses when loads were turned off, and provisions for permanent connections were not available. For utility-interactive applications, it was found that the uninterruptible power supply (UPS) inverters were costly, inefficient, and could not work with the wide input voltage window presented by PV modules. They also lacked controls for MPPT, and they needed extensive modifications for the required wake-up and shut down functions for the diurnal cycles of the PV power source [42].

3. Global PV module and its electrical performance

The production of solar cells has grown at an average annual rate of 37% in the past decade, i.e. from 77.6 MWp in 1995 to 1817.7 MWp in 2005, and at an average annual rate of 45% in the past 5 years (from 287.7 MWp in 2000 to 1817.7 MWp in 2005) [2]. Fig. 1 shows the production capacity for some countries and regions in the year of 2005.

One feature of the global PV industry is that PV-generated electricity is replacing other forms of electricity at an increasingly high rate. This is most evident in the growth-rate for grid-connected electricity, which has become the dominant market for PV-generated electricity as shown in Fig. 2. Other applications for PV-generated electricity include communication and signaling, special commercial and industrial applications, rural off-grid systems, consumer use and large-sized power plants not connected to the grid.

The electrical energy produced by a solar cell at any time instant depends on its intrinsic properties and the incoming solar radiation. Details of the solar cell physics can be found in standard texts [47]. The algorithm adopted in ESP-r, as described below, was developed as a result of the JOULE project PV-HYBRID-PAS funded by the European Commission and is reported in [48]. The diode factor (DF) of a PV array with m number of cells in parallel and n cells in series is defined as

$$\mathrm{DF} = \frac{e}{kT_{\mathrm{ref}}} \frac{V_{\mathrm{mp}} - V_{\mathrm{OC}}}{n} \left[\ln\left(\frac{I_{\mathrm{Sc}} - I_{\mathrm{mp}}}{I_{\mathrm{Sc}}} \right) \right]^{-1} \tag{1}$$

At a particular cell temperature T_c, the un-illuminated current flow in the p–n junction is then:

$$I_o = 2^{T_c - T_{\mathrm{ref}}/C_T} \frac{I_{\mathrm{Sc}}}{m} \left[1 - \exp\left(\frac{e(V_{\mathrm{OC}}/n)}{kT_{\mathrm{ref}}\mathrm{DF}} \right) \right]^{-1} \tag{2}$$

I_o is known as the diode current. In the equation, C_T is an empirical constant depending on the impact of cell temperature output. This normally carries a value of 10 for crystalline silicon PV modules,

Table 1
Definitions of some terminologies as they pertain to this paper.

Application specific integrated circuit (ASIC)	A highly integrated circuit package containing hundreds of logic functions that is modified by burning-away internal paths to produce application specific circuit functions. ASICs are used to provide design flexibility and to reduce cost and parts count in the control section of an inverter.
ac PV building block	A complete, environmentally protected PV modular system consisting of a PV module, a complete integrated inverter enclosed with a housing eliminating exposure of any dangerous voltage and generally doubling as the module frame or mounting structure that also encloses all of the necessary ac bus work, interconnects, communication, surge protection and terminations [44].
ASTM	American Standards for Testing Materials.
Azimuth	An Azimuth different from 180° (south) shifts the theoretical power peak toward east or west according with the orientation of the PV generator.
Bi-directional inverter	An inverter that can be operated in all four quadrants of the voltage/current regime hence may function as an inverter or as a rectifier by applying the proper drive signals. Power flow may be in either direction.
Burden	The impedance (load) of the circuit connected to the secondary winding of an instrumentation transformer. *Note*: for voltage transformers it is convenient to express the burden in terms of the equivalent volt-amperes and power factor at a specified voltage and frequency (from IEEE Std. 100-1996) [43].
CHP or micro-CHP	Combined heat and power or the micro-combined heat and power.
Converter	A general term used to describe a device for changing direct current power to alternating current power or vise versa or from one frequency to another.
Current-controlled inverter	An inverter designed to convert dc power to ac power where the output current is controlled and unaffected by output voltage fluctuations. Typically used in utility-interactive applications where voltage is controlled by the utility.
Disconnect switch	A switching device that breaks an electrical circuit. These devices may have ac or dc voltage and current ratings and may or may not be rated for breaking under load. Disconnect switches usually provide a visible break, and may have a locking feature to provide control over the status of the disconnect switch.
Energy efficiency	The ratio of output energy to input energy during an identified period.
Electromagnetic interference or compatibility (EMI/EMC)	Generally refers to electromagnetic interference (radio frequencies) produced by a device and electromagnetic compatibility (EMC) of the device. Inverters must not emanate excessive EMI or be susceptible to normal EMI. EMI may be radiated as a radio wave or conducted on the ac and dc lines.
ESL	Equivalent series inductance, a term associated with the inductance associated with the construction and leads of capacitors.
ESR	Equivalent series resistance, a term associated with the power losses of a capacitor.
ETO	Emitter-turn-off thyristor: a new solid-state switch consisting of a thyristor device under development that is configured to facilitate device turn-off via emitter signals and generally switches faster than the commercial GTOs and can handle more power than IGBTs.
Field-effect transistor (FET)	Field-effect transistor: a solid-state device that uses a voltage field to control the current flow through it. Devices used in today's inverters are usually metal-oxide-silicon FETs (MOSFETs) and are generally used when the dc voltage is less than 100 V. They can easily be wired in parallel with each other to increase the current/power rating of the inverter.
HALT	Highly accelerated life tests that are conducted in a manner to reveal component and package layout weakness that have been related to premature failure mechanisms and mean-time-to-first-failure (MTBF).
IGBT	Insulated gate bi-polar transistor: a solid-state switch that combines the advantages of the FET and a bi-polar transistor. It requires low control power but has the advantages of low losses when in the "on" state. IGBTs are generally used when input voltages are greater than 100 V. IGBTs have a wide range of capabilities and are now being integrated with built-in drivers and self-protection.
Interconnection	The equipment and procedures necessary to connect a power generator to the utility grid. IEEE Std. 100-1996 [43] Def: the physical plant and equipment required to facilitate the transfer of electric energy between two or more entities. It can consist of a substation and an associated transmission line and communications facilities or only a simple electric power feeder.
Inverter	A device designed to convert dc power to ac power. Inverters are also commonly referred to as power conditioning systems and power conditioners in PV applications. Inverters are often referred to as static power converters (SPC) in standards documents.
Islanding	A condition in which a portion of the utility system that contains both load and distributed resources remains energized while isolated from the remainder of the utility system [41]. Islanding is the electrical phenomenon in a section of a power network disconnected from the main supply, where the loads in that disconnected section are entirely powered by PV systems and where the voltage and frequency are maintained around nominal values. At the point of disconnection of an island it is essential that the active power and reactive power at the point of disconnection be very close to zero. The disconnection of the islanding must also happen without introducing a short circuit between the phases and/or between one phase and ground. Any fault forces the voltage to a very low value and all PV systems will immediately switch off and islanding will not occur. Islanding is a balanced condition in a disconnected part of a power network where the load is sustainable powered by the connected PV systems. A balanced condition of only a few seconds is not categorized as a sustainable power balance. Within the IEA Task V working group a period of 5 or more seconds is treated as a possible islanding.
Line-commutated inverter	An inverter designed to be attached to the utility grid or other ac source that requires the switch current to pass through zero in order to turn the switching devices "off." Several versions of small, single-phase, line-commutated inverters were used early in the PV program. Line-commutated inverters are still used for some three-phase intermediate-sized and all large (>500 kW) inverters.
Maximum power point tracker (MPPT)	Circuitry associated with utility-interactive inverters (and some larger stand-alone) that continuously adjust the dc operating point to obtain the maximum power available from a PV array at any given time.
Modular inverter	An inverter design that is compatible with the paralleling or summing with one or more inverters of the same or similar design.
MOSFET	Metal oxide field-effect transistor.
MOV	Metal oxide varistor, a commonly used surge suppression device.
MSD	Mains monitoring units with allocated all-pole switching devices connected in series (ENS).
MTBF	Mean-time before failure.
Multi-level inverter	An inverter using a circuit topology that switches segments of the energy source in and out of the output circuit in order to synthesize a current sourced low frequency (typically 50 or 60 Hz) sine waveform.
NEC	National Electrical Code, a publication of the National Fire Protection Association.

Table 1 (*Continued*)

NFPA	The National Fire Protection Association, the organization responsible for the National Electrical Code and numerous other installation related codes.
Non-islanding inverter	An inverter defined in IEEE 929 as one that will cease to energize the utility line in 10 cycles or less when subjected to islanded loads that are $>\pm 50\%$ mismatch to inverter real-power output and power factor is less than 0.95 [45]. Alternatively, a disconnection from the line is required within 2 s if the load to inverter match is $<50\%$, the power factor is >0.95 and the quality factor is 2.5 or less.
Point of common coupling	The point at which the electric utility and the customer interface occurs. Typically, this is the customer side of the utility revenue meter. *Note*: in practice, for building-mounted PV systems (such as residential PV systems) the customer distribution panel may be considered the PCC. This is for convenience in making measurements and performing testing.
PCS	Power conditioning subsystem or power conditioning system (see SPC the IEEE definition associated with inverters)
Performance test conditions (PTC)	A fixed set of ambient conditions that constitute the dry-bulb temperature (20 °C), the in-plane irradiance (1000 W/m^2 global for flat-plate modules, 850 W/m^2 for concentrators), and wind speed (1 m/s) at which electrical performance of the PV system is reported.
Power conditioning unit (PCU)	A device that converts the dc output of a PV array into utility-compatible ac power. The PCU (inverter) may include (if so equipped) the array maximum power tracker, protection equipment, transformer, and switchgear. See also inverter, power conditioning subsystem (PCS), and static power converter (SPC). *Note*: the term ''Inverter'' is most commonly used.
PVUSA	PVs for utility scale applications.
PWM	Pulse width modulated: a method used in self-commutated inverters to generate a synthesized waveform (e.g. a 50- or 60-Hz sine wave) through a combination of varying the duration of time that the switches in a bridge are turned ''on'' and ''off.'' PWM switching frequencies may be constant or vary. PWM offers the advantages of using high-frequency transformers and much smaller filter components. PWM frequencies may range from 5 to 100 kHz for PV inverters. Many utility-interactive inverters use PWM.
RCMU	Residual current monitoring unit.
SAD	Silicon Avalanche device, a transient surge suppression device.
SBIR	Small business innovative research program conducted by several programs of the U.S. Government.
Self-commutated inverter	An inverter that uses switches and controls that may be turned ''on'' or ''off'' at any time. Generally this inverter uses a PWM method to generate a synthesized waveform. Self-commutated inverters may be utility-interactive or stand-alone. They may be voltage controlled or current controlled.
Silicon controlled rectifier (SCR)	A semiconductor that is a member of the thyristor family. It cannot be switched from ''on'' to ''off'' with gate controls unless current through it passes below a holding threshold (typically through zero). These devices are typically used in line-commutated inverters.
Supervisory control and data acquisition (SCADA)	Equipment used to monitor and control power generation, transmission, and distribution equipment (IEEE Std. 100). Def.: A system operating with coded signals over communication channels so as to provide control of remote equipment (using typically one communication channel per remote station). The supervisory system may be combined with a data acquisition system, by adding the use of coded signals over communication channels to acquire information about the status of the remote equipment for display or for recording functions.
Static power converter (SPC)	Terminology used in some standards for any static power converter with control, protection and filtering functions used to interface an electric energy source with an electric utility system. Sometimes referred to as power conditioning subsystem (PCS) or power conditioning units. Typically sold as inverters for PV applications.
Stand-alone inverter (S-A)	An inverter designed to operate with the loads connected directly to its output and independent of any other ac power source. This inverter requires a battery at the input to provide dc voltage regulation and surge currents. The stand-alone inverter provides frequency and voltage regulation, over current protection and surge capabilities for the loads. The S-A inverter must be a self-commutated, voltage-controlled inverter so that loads can be operated within their specified voltages.
Stand-by loss	For a utility-interactive power conditioner, this is the active and reactive power drawn from the utility grid when the power conditioner is in stand-by mode.
String inverter	An inverter designed to use a single PV string of modules for its input. The ac output of many inverters can be combined and fed to a common transformer. String inverters can be used to reduce dc wiring and protection costs and to improve redundancy of a large system.
Standard reporting conditions (SRC)	For PV performance measurements, a fixed set of conditions that constitute the device temperature, the total irradiance, and the reference spectral irradiance distribution to which electrical performance data are translated (see ASTM Std. E 1328).
Standard test conditions (STC)	A particular set of SRC defined as 1000 W/m^2 irradiance, 25 °C cell temperature, and Air Mass 1.5 spectrum (see ASTM Std. E 1328).
TEAM-UP	Technology experience to accelerate markets in utility PVs.
Thyristor	A term used for a family of semiconductor switching devices characterized by bi-stable switching (either ''on'' or ''off'') through internal regenerative feedback. Some thyristors can be forced to turn ''off'' but many will turn ''off'' only when current through it falls below a holding current threshold.
Tilt	Higher values of tilt angle usually increase the power production in winter and decrease it in summer. Furthermore, when the sun covers a large path (summer period) a high tilt angle restricts the production curve. When tilt is equal to 90° the maximum theoretical visibility of the sun path is limited to 180°.
Transistor (bipolar transistor)	A semiconductor device characterized by output current that is dependent upon an input current. They exhibit low forward losses but require more drive power than FETs or IGBTs. Several early inverters used bi-polar power transistors as switching devices.
TSD	Transient surge device sometimes referred to as TSSD or transient surge suppression device.
Utility	For this document, the organization having jurisdiction over the interconnection of the PV system and with whom the owner would enter into an interconnection agreement. This may be a traditional electric utility, a distribution company, or some other organization. IEEE Std. 100-1996. Def: An organization responsible for the installation, operation, or maintenance of electric supply or communications systems.
Utility-interactive inverter (U-I)	An inverter designed to be connected to the utility grid or other stable ac source. This inverter does not require dc energy storage and usually incorporates a MPPT to maximize power delivered to the grid. It may be self- or line-commutated and may be voltage-or current-controlled. Non-islanding requirements now apply to U-I inverters in the United States, some European countries and in Japan.
VJFET	Vertical-junction field-effect transistor: Generally referring to the physical construction of a field-effect (SiC) device as referred to in this report.
Voltage-controlled inverter	An inverter designed to convert dc power to ac power where the output voltage is controlled. Typically used in stand-alone applications since the output voltage must be regulated within the inverter. Voltage controlled inverters are also used as utility-interactive where they employ a line-tie impedance to limit current flow between the inverter and the utility.

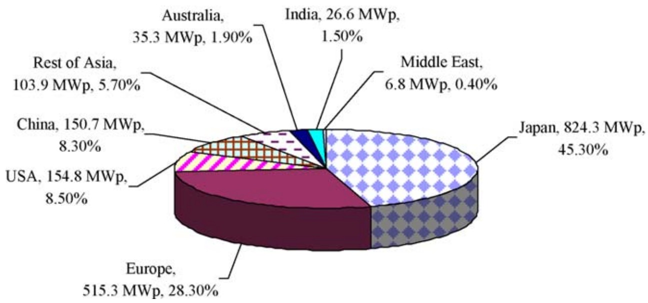

Fig. 1. Global PV cell manufacturing capacity (MWp) by country or region in 2005 [46].

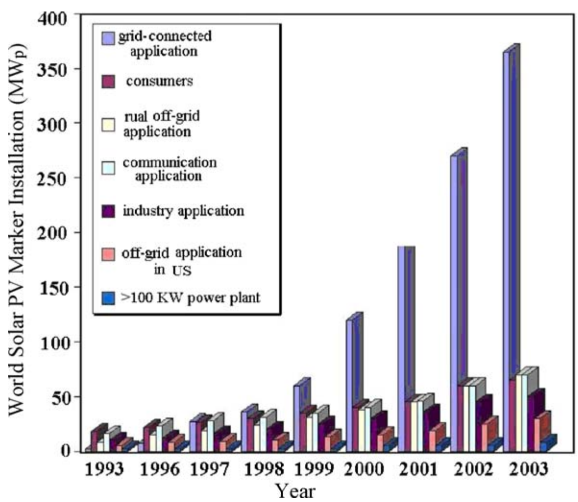

Fig. 2. Growth in world solar PV installation for different uses, 1993–2003.

and a higher value for amorphous silicon modules which are less sensitive to temperature change.

If Q is the instantaneous solar irradiance falling on the PV surface, the light generated current (I_L) is given by

$$I_L = \frac{Q}{Q_{ref}} \frac{I_{Sc}}{m} \tag{3}$$

The PV panel can be operated at the MPPT where, its voltage, occurring at the knee of the characteristic I–V curve of the current time step, can be determined by iteration using the following equation:

$$1 + \frac{I_L}{I_o} = \exp\left(\frac{eV_{mpp}}{kT_c \mathrm{DF}}\right)\left(1 + \frac{eV_{mpp}}{kT_c \mathrm{DF}}\right) \tag{4}$$

The panel power output is

$$P = \left[V_{mpp} I_L - V_{mpp} I_o \exp\left(\frac{eV_{mpp}}{kT_c \mathrm{DF}} - 1\right)\right] nmN \tag{5}$$

with the corresponding electricity generating efficiency given by

$$\eta_c = \frac{P}{Q} \times 100\% \tag{6}$$

PV power generating systems can be divided into independent PV systems and grid-connected PV systems, and further divided according to the installation environment. Stand-alone PV systems are called off-grid PV systems. Their applications include rural household power supply, rural central power plants and power supply for communication, cathodic protection and lighting. Small and medium-sized stand-alone PV systems of 5–100 kWp, and large-sized systems of greater than 100 kWp, have been extensively disseminated. The design of central stand-alone PV power generating systems is becoming optimized and intelligent, and advanced techniques are being adopted.

Table 2
Growth rates in the market share of grid-connected PV electricity generation, 1996–2005 [2].

Year	Annual growth rate (%)
1996	7.9
1997	21.3
1998	23.5
1999	29.9
2000	41.7
2001	50.4
2002	51.4
2003	55.5
2004	65.9
2005	~75

Inverters in stand-alone systems must regulate their output ac bus voltages by supplying current as needed to maintain voltage, and battery energy storage is usually included to address power demand surges, store generated power during low demand, and continue to supply power to the load during cloudy or night time conditions. The technology exists to incorporate similar features into grid-tied PV inverters, but doing so would drive up the cost of photovoltaic electric power compared to existing real-power-optimized grid-connected PV power systems [49].

4. Grid-connected PV systems

Grid-connected PV systems include building integrated PV (BIPV) systems and terrestrial PV systems (including PV power plants in saline-alkali land, tideland and desert). At the scale of the entire interconnected electric power grid, generated electric power must be consumed within milliseconds of being generated. Excess power can be accumulated with energy storage systems such as pumped hydro, but conventional energy storage systems respond much more slowly than the load changes so throttling back on peaking generation is used to stabilize the power flow into and out of the grid. In addition, when the load on the utility grid reaches new peak levels, the system operators must start activating every available generating source and even minor throttling back of generation may cause the grid voltage to collapse.

Table 2 gives the growth rates in the market share of grid-connected PV electricity generation from 1996 to 2005 [2]. Table 3 represents the grid-connected solar rooftop programs in 2005, and the references details are available in [45].

Grid-connected solar PV continued to be the fastest growing power generation technology, with a 55% increase in cumulative installed capacity to 3.1 GW, up from 2.0 GW in 2004. More than half of the annual global increase occurred in Germany, which saw over 600 MW of PV installed in 1 year (Fig. 3). Grid-connected solar PV increased by about 300 MW in Japan and 70 MW in the United States. Several milestones occurred in 2005, such as the commissioning of the world's largest solar PV power plant, 10 MW total, in Germany, and many large commercial installations of tens and hundreds of kilowatts (kW) each. German cumulative PV capacity exceeded Japan's for the first time. Including off-grid applications, total PV existing worldwide increased to 5.4 GW, up from 4.0 GW in 2004.

The major elements of a grid-connected PV system that does not include storage are shown in Fig. 4. The inverter may simply fix the voltage at which the array operates, or (more commonly) use a maximum power point tracking function to identify the best operating voltage for the array. The inverter operates in phase with the grid (unity power factor), and is generally delivering as much

Table 3
Grid-connected solar rooftop programs, 2005 (MW except for existing number of homes).

Program and years	Added 2002	Added 2003	Added 2004	Added 2005	Existing 2005	Existing homes 2005	Supporting policies
Japan: residential program (1994–2004)	140	170	230	–	830 (by 2004)	250,000	"Sunshine" program capital subsidy started at 50% in 1994, and declining to 10% by 2003
Japan: other programs and private	40[a]	50[a]	40[a]	310[a]	610[a,b]	70,000	NEDO R&D programs, commercial installations, local Government installations, and unsubsidized residential
Germany (1999–2003 and 2004 to present)	80[a]	150[a]	490[a]	600 (or more)[a]	1500[a]	250,000[c]	100,000 roofs program provided low-interest loans and feed-in tariff of €0.50/kWh to 2003. In 2004, tariffs set €0.45–0.62/kWh
California programs (1998–2011)	n/a	n/a	40	55	140	30,000	Initial state program subsidy of $4.50/W (ac) declined to $2.80/W (ac) by 2005. Utility (SMUD, LADWP) programs
Other U.S. programs	n/a	n/a	10	10	100	20,000	
Other EU programs	n/a	n/a	n/a	40	200	40,000	
Other	n/a	n/a	n/a	30	40		
Total added	270	400	800	1050			
Cumulative					3100	650,000	

[a] An unknown share of this data is off-grid. Amounts for Germany are likely quite small. The amount for Japan is assumed to be about 150 MW cumulative as of 2005.
[b] Data is reported by METI and JPEA on a fiscal year basis, ending in March. So the 2005 figures include installations from January to March 2006.
[c] There were more than 200,000 total PV installations in Germany, according to the German solar energy association.

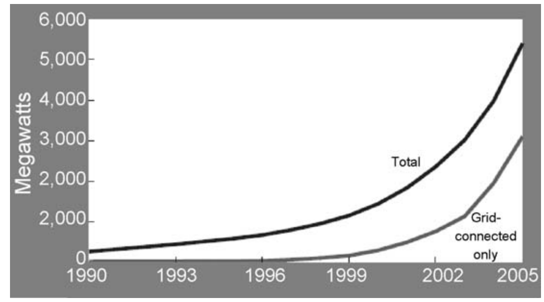

Fig. 3. Solar PV, existing world capacity, 1990–2005 [50].

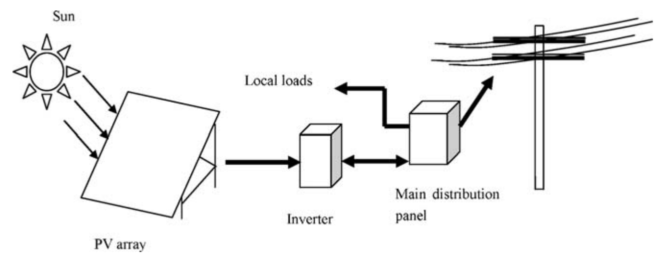

Fig. 4. Grid-connected PV power system with no storage.

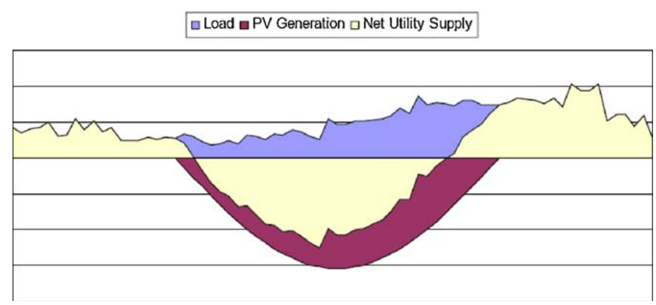

Fig. 5. Power flows required to match PV energy generation with load energy consumption [49].

power as it can to the electric power grid given the available sunlight and temperature conditions. The inverter acts as a current source; it produces a sinusoidal output current but does not act to regulate its terminal voltage in any way. The utility connection can be made by connection to a circuit breaker on a distribution panel or by a service tap between the distribution panel and the utility meter. Either way, the PV generation reduces the power taken from the utility power grid, and may provide a net flow of power into the utility power grid if the interconnection rules permit [49].

Fig. 5 shows the daytime power production (peak of generation "hump") needed to match daily energy production (area of "hump") with daily load energy (blue area) can exceed the peak load power flow. For this residential load example, the peak load power flow is a double peak in late evening, which highlights the misalignment that can occur between residential load and PV generation.

All the grid-connected PV power plants that have been successfully demonstrated in China are client grid-connected modules with low voltage. Their power generation capacity is relatively small and they do not dispatch power through the network; hence they have little impact on the normal running of the power network.

The first grid-connected BIPV system in Hong Kong was installed on the three walls and the roof of a plant room on a

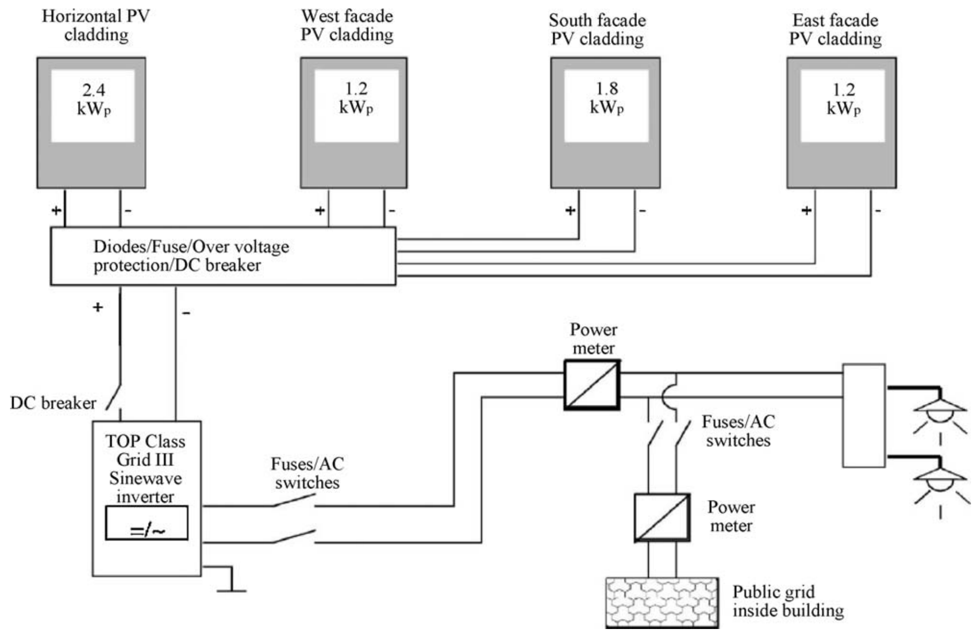

Fig. 6. Schematic diagram of the first grid-connected building-integrated PV system in Hong Kong [51].

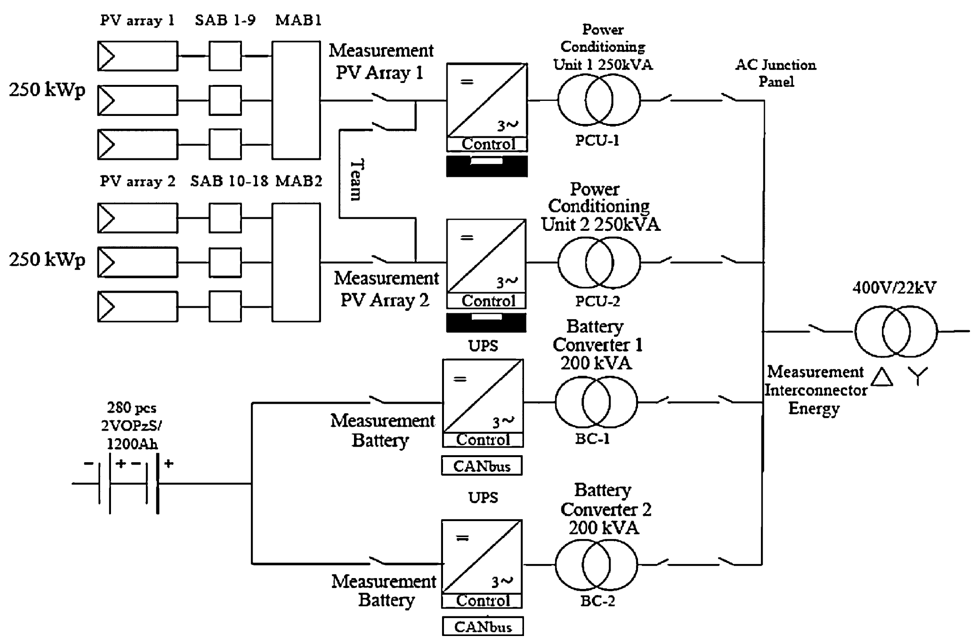

Fig. 7. Schematic block circuit diagram of the PV system [52].

building, PV panels integrated on the horizontal roof and the vertical east, west and south facades. An air gap was designed between the massive wall and the PV panels for the three vertical facades so that natural ventilation effect can be measured. The system consists of 100 PV panels (made by BP) with each 80 Wp and a TCG4000/6 inverter, in which the 20 panels face east, 22 south, 18 west and 40 on the top. The system was rated at 8 kW with output dc voltage of 75–105 V, output ac voltage of 220 V. The schematic diagram of the system is shown in Fig. 6.

The overall energy efficiency of this system was found as 9% while the energy efficiency of the inverter is 86–87%. The experimental results have shown that on sunny days the system produces sufficient electricity for the lighting circuit of a 250 m^2 floor area. The horizontal roof PV panels produce more power compared with the same surface area of PV panels on the walls. Comparisons between theoretical simulation results and site measurements agree well for the natural ventilation design. Analysis shows that grid-connected BIPV application is still not economical, but the technology should be promoted due to its huge potential in terms of environmental protection and future development [51].

Performance of a 500 kW_P grid-connected PV system at Mae Hong Son Province, Thailand, was summarized by [52]. The PV system is fully monitored to assess the potential of PV technology and performance of the system with the local power grid (Fig. 7). The monitoring system was designed to meet guideline of standard IEC 61724 and within the framework of the International Energy Agency PV Power System (IEA-PVPS) Program TASK 2. The

quantities used to assess the performance of the grid connection were given as

$$\text{Array yield}, \quad Y_A = \frac{E_A}{P_O}, \text{ kWh/kW}_p\text{ d} \tag{7}$$

$$\text{Reference yield}, \quad Y_R = \frac{H_T}{G_{STC}}, \text{kWh/kW}_p\text{ d} \tag{8}$$

$$\text{Final yield}, \quad Y_F = \frac{E_{PV}}{P_O}, \text{kWh/kW}_p\text{ d} \tag{9}$$

$$\text{Capture losses}, \quad L_C = Y_R - Y_A, \text{kWh/kW}_p\text{ d} \tag{10}$$

$$\text{System losses}, \quad L_S = Y_A - Y_F, \text{kWh/kW}_p\text{ d} \tag{11}$$

The efficiency of the PV array system ranged from 9 to 12%. The efficiency of the power conditioning units (PCU) ranged from 92 to 98%. The final yield (YF) ranged from 2.91 h/d (March 2004) to 3.98 h/d (April 2004) and the performance ratio ranged from 0.70 to 0.90.

The above mentioned losses are associated with several factors such as: cells operating out of the STCs; voltage drop in the dc cables and protection diodes; dirt; partial shade; dispersion of parameters among the PV modules; operation voltage out of the maximum power point (MPP); spectrum and angle of incidence. Not all the mentioned aspects can totally be represented in terms of simulations. Only through the aid of experimental data it is possible to analyze the magnitude of the losses involved in those systems, for the subsequent improvement of the forecasts accomplished in the project stage.

Losses due to electric conductors: these losses are important in dc, when the voltage is low. It is crucial to conveniently size the conductor sections so that the voltage drop is less than 1.5%. It is also important to place the generators close to the inverters, to work at the maximum dc voltage that the panels and the inverters can withstand, to increase the conversion performance, and to reduce ohmic losses [53].

Also there are many factors affecting PV power output such as:

- Tilt and azimuth of the PV generator;
- buildings, mountains, trees, etc. which may cause shadowing;
- alignment of PV arrays that may cause reciprocal shadowing.

Variations in the above mentioned parameters may cause a number of effects in the energy distribution. It is important to know the distribution system configurations, distribution system equipment, required protection relays and so on because they are strongly related to the requirement for grid interconnection equipment. The distribution line configuration for each participating country of Task V were studied and summarized as follow:

(i) Voltage level and network scheme (HV transmission, HV distribution, MV distribution and LV distribution); (ii) capacity of transformers–feeders–capacitors (transformer, feeders per transformer, impedance, average length, number of switches per feeder, number of sectionalize per feeder, capacitor for p.f. improvement, average number of customer per feeder per phase for LV and power rating of customer for LV); (iii) protective device (protective device installed in the public network, reclosing and protective coordination with independent producer) and (iv) type and setting levels of the interface devices installed in the independent producer's network – operation criteria – (voltage fluctuation, voltage regulation, temporary supply and work method for fault repair).

4.1. Power value

The power value may be defined as the economic value of the power produced, given the plant location and its trend of production. This is because the power value is affected by the distance between the power station and the load (decentralized production near the loads is typical for PV) and by the match/mismatch conditions of the production with the trends of the loads in low voltage (LV) branches.

The power value varies instant by instant depending on the present level of power production and surrounding load conditions. The power value of PV generation in the grid takes into account the reduction of energy production costs (savings in fuel consumption, O&M, etc.), the transportation costs and, in some cases, the risk reduction as regards the possible situations of scarcity in given periods (peak hours).

In accordance with the given definitions, a calculation or esteem (if all necessary data are not completely available) of the power value for the PV must consider the following items [54]:

$$\begin{aligned}\text{Power value} \quad &= \text{Market price of electricity}\\ &+\text{Savings in reduction of joule losses (i)}\\ &+\text{Improvement of the quality of service (ii)}\\ &+\text{Improvement of the quality of service (ii)} + \text{Improvement of the continuity of service (iii)}\\ &+\text{Savings of investment for additional distribution equipment (iv)}\\ &+\text{Savings of investment for additional power production } (\nu)\\ &+\text{Reduction of environmental impacts } (\nu\text{i})\end{aligned} \tag{12}$$

It is possible to note that the power value related to the topics from i to ν strongly depends from the possibility to modify the LV consumption curve in order to flatten it. Usually, this effect takes place when the trends of loads and PV production are quite in phase and there are not consumption's peaks in the evening or night.

4.2. Ratio between load and PV power

The ratio between load and PV power can be calculated by determining the ratio between the PV power and the power in every phase of every Bay. In other words how big should the PV system be to equal the power consumed in the power network. The ratio varies as the loading of the power network and the output power of the PV system varies in time. The ratio is calculated every second using the following equation [55]:

$$\text{Ratio} = \frac{P_{load}}{P_{PV}} \tag{13}$$

In an attempt to reduce the computing time to acceptable levels, the load current and PV current can be used instead of the active power. This assumption may be made since the power factors of both the PV system and the loading of the network are relatively constant. Also, the ratio is an indication about possible penetrations levels for which islanding may be relevant. Then Eq. (1) becomes:

$$\text{Ratio} = \frac{I_{load}}{I_{PV}} \tag{14}$$

It is observed that there is not a definitive orientation regarding what relationship between the inverter's rated power and the PV

generator's maximum power should be used, since it depends on a series of factors intrinsic of each specific installation [56–63]. On the other hand, the difference between the PV generator's maximum power under STC and the power that it really supplies, coupled to the fact that the PV generator operates most of the time out of the test conditions, usually is used as excuse for over-sizing the maximum power of the PV generator in relation to the inverter's rated power [63,64]. However, it should be adverted that the difference between the values of the maximum power and the real-power of the PV generator has been decreasing and, in some cases, becoming positive [63]. Unfortunately, there are few works based in experimental results of systems operating with different relative capacities, P^0_{Inv}/P^0_{PV}. The most common is to find operational results in kWh/kWp, without mentioning the relationship between the inverter's capacity and the capacity of the PV generator [65–67].

Ref. [68] presented operational results of a 11.07 kWp grid-connected PV system. The system was made up by eight groups with different relationships between the inverter's rated power and the PV generator's maximum power (P^0_{Inv}/P^0_{PV}). The relationship P^0_{Inv}/P^0_{PV} for each one of the groups is based in the measured power values (VM) of each PV generator. The obtained results led to the verification that the different studied relationships, P^0_{Inv}/P^0_{PV} between 55 and 102%, do not affect significantly the final yields (YF).

5. Potential problems associated with high penetration levels of grid-tied PV

An extensive literature search was conducted to collect the available information on expected problems associated with high penetration levels of grid tied PV. The penetration level is defined as the ratio of nameplate PV power rating (W_p) to the maximum load seen on the distribution feeder (W). The results of that literature survey are presented below.

Ref. [69] examined cloud transient effects if the PV were deployed as a central-station plant, and it was found that the maximum tolerable system level penetration level of PV was approximately 5%, the limit being imposed by the transient following capabilities (ramp rates) of the conventional generators. Ref. [70] focus on the operating experience of the Southern California Edison central-station PV plant at Hesperia, CA, which reported no such problems, but suggests that this plant had a very "stiff" connection to the grid and represented a very low PV penetration level at its point of interconnection.

Ref. [71] dealt with voltage regulation issues on the Public Service Company of Oklahoma system during the passage of clouds over an area with high PV penetration levels, if the PV were distributed over a wide area. At penetration levels of 15%, cloud transients were found to cause significant but solvable power swing issues at the system level, and thus 15% was deemed to be the maximum system level penetration level.

A study in paper [72] describing the harmonics at the Gardner, MA PV project. The 56 kW of PV at Gardner represented a PV penetration level of 37%, and the inverters (APCC SunSines) were among the first generation of "true sine wave" PWM inverters [73]. All of the PV homes were placed on the end of a single phase of a 13.8 kV feeder. The PV contribution to voltage distortion at Gardner was found to be about 0.2%, which was far less than the contributions made by many customer loads [72]. It was thus concluded that harmonics were not a problem as long as the PV inverters were "well designed". This paper also mentions the potential value of PV systems being able to provide reactive power to keep the power factor of a feeder approximately constant.

The Gardner, MA PV project [73] looked at four areas: the effect on the system in steady state and during slow transients (including cloud transients); how the concentrated PV responded under fast transients, such as switching events, islanding, faults, and lightning surges; how the concentrated PV affected harmonics on the system; and the "overall performance of distribution systems", in which the total impact of high-penetration PV was evaluated. The final conclusion is that the 37% penetration of PV at Gardner was achieved with no observable problems in any of the four areas studied.

Ref. [74] attempted to quantify the impact of geographic distribution of PV on allowable PV penetration level, at the system level, using a utility in Kansas. The study concluded that under the conditions studied, the utility's load-following capability limited PV penetration to only 1.3% if the PV were in central-station mode, with the limitation being caused by unscheduled tie-line flows that unacceptably harmed the utility's economics. However, the allowable penetration rose to 36% if the PV is scattered over a 1000 km^2 area, because of the "smoothing" effect of geographic diversity.

Ref. [75] studied the impact of high penetrations of PV on grid frequency regulation which responding to synthetically generated short-term irradiance transients due to clouds. The study looked at system frequency regulation, and also at the "break-even cost" which accounts for fuel savings when PV is substituted for peaking or base load generation and the cost of the PV. This study concluded that, the break-even cost of PV is unacceptably high unless PV penetration reaches 10% or so. The thermal generation capacity used for frequency control increases more rapidly than first thought, and that a 2.5% increase in frequency control capacity over the no-PV case is required when PV penetration reaches 10%. For PV penetration of 30%, the authors found that a 10% increase in frequency regulation capacity was required, and that the cost of doing this swamps out any benefit. Based on these two competing considerations, the authors conclude that the upper limit on PV penetration is 10%.

The International Energy Agency (IEA) has produced a series of reports on Task V of the PV power systems (PVPS) implementing agreement. Islanding, capacity value, certification requirements, and demonstration project results were all the subject of investigations, but the one that is of primary importance here dealt with the subject of voltage rise [76]. This report focused on three configurations of high-penetration PV in the low-voltage distribution network (all PV on one feeder, PV distributed among all feeders on an MV/LV transformer, and PV on all MV/LV transformers on an MV ring). This study concludes that the maximum PV penetration will be equal to whatever the minimum load is on that specific feeder. That minimum load was assumed to be 25% of the maximum load on the feeder in [76], and if the PV penetration were 25% of the maximum load, then only insignificant over voltages occurred. Any higher PV penetration level increased the over voltages at minimum loading conditions to an unacceptable level.

Two major studies [77,78] concentrated on distributed generators interfaced to utilities through inverters, and larger-scale system impacts and rotating distributed generation (DG), but still with several results on inverter-based DG. The first study [77] concluded that for DG penetration levels of 40%, such that the system is heavily dependent on DGs to satisfy loads, voltage regulation can become a serious problem. The sudden loss of DGs, particularly as a result of false tripping during voltage or frequency events, can lead to unacceptably low voltages in portions of the system. During periods of low load but high generation and with certain distribution circuit configurations, the reverse power flow condition could cause malfunctions of the series voltage regulators. Again, voltage regulation becomes a problem.

A voltage regulation function, implemented through reactive power control, would enable inverter-based DGs to be much more

Table 4
Summary of maximum PV penetration levels suggested in the literature.

Maximum PV penetration level	Cause of the upper limit	Reference number
5%	Ramp rates of main-line generators. PV in central-station mode.	[69]
15%	Reverse power swings during cloud transients. PV in distributed mode.	[71]
No limit found	Harmonics.	[72]
>37%	No problems due to clouds, harmonics, or unacceptable responses to fast transients were found at 37% penetration. Experimental + theoretical study.	[73]
Varied from 1.3 to 36%	Unacceptable unscheduled tie-line flows. The variation is caused by the geographical extent of the PV (1.3% for central-station PV). Results particular to the studied utility because of the specific mix of thermal generation technologies in use.	[74]
10%	Frequency control vs. breakeven costs	[75]
Equal to minimum load on feeder	Voltage rise. Assumes no load tap changing's in the MV/LV transformer banks.	[76]
<40%	Primarily voltage regulation, especially unacceptably low voltages during false trips, and malfunctions of series voltage regulators.	[77,78]
5%	This is the level at which minimum distribution system losses occurred. Note that this level could be nearly doubled if inverters were equipped with voltage regulation capability.	[79]
33% or ≥50%	Voltage rise. The lower penetration limit of 33% is imposed by a very strict reading of the voltage limits in the applicable standard, but the excursion beyond that voltage limit at 50% penetration was extremely small.	[81]

beneficial to the grid than they currently are. Unfortunately, this function would interfere with most anti-islanding schemes as they are presently implemented. Inverter-based DGs do not contribute significantly to fault currents, and thus did not adversely impact coordination strategies for fuses and circuit breakers.

The study notes that the short-duration fault current contribution of small distributed inverter-based DGs is smaller than that of distributed induction machines. However, it also points out that this might not always be true if the DG is connected at a point where the utility series impedance is unusually high. These conclusions may not remain valid if the voltage regulation controls suggested above are implemented.

The inverter-based DGs did not respond adversely to high-speed transients such as those caused by capacitor switching, and thus did not degrade the system's response in such cases. For widely dispersed DGs, modern positive feedback-based anti-islanding appears to be effective in eliminating islands without causing serious impacts on system transient performance, but the complexity of the subject indicates that more study is needed.

Significant impacts were observed when DG penetration levels were between 10 and 20% [78]. This study suggests that active anti-islanding, particularly involving positive feedback on frequency has a negative but minor impact on system dynamic behavior.

In 2006, Ref. [79] examined the impact of DGs on distribution system losses, as a function of penetration level and DG technology. It concluded that distribution system losses reach a minimum value at DG penetration levels of approximately 5%. But the distribution system losses begin to increase as penetration increases above that level. The reasons for this are not clear, but the general result that there was a penetration level at which distribution losses were minimized was consistent across all DG technologies. The penetration level at which minimum losses occurred was nearly doubled if voltage regulating, variable power factor inverters were used.

Another report in 2006 was produced by a European consortium called distributed generation with high penetration of renewable energy sources (DISPOWER) that includes Universities, research institutes, manufacturers, and representatives of several segments of the utility community [80]. This report examined many different types of DG in many configurations. Items in the DISPOWER report that are of specific interest here include the following. The report describes a Power Quality Management System (PQMS), which uses TCP/IP as its protocol and Ethernet cables as the physical communications channel. Initial field tests appear to be promising. One section of the report deals specifically with problems expected as DGs approach high penetration levels. The authors studied both radial and mesh/loop distribution system configurations and concluded that the mesh/loop configuration has significant advantages for mitigating the problems associated with high DG penetration. They also pointed out that harmonics increased slightly when the DGs were present, but never did they reach a problematic level. This study does not include a suggestion of a maximum penetration level.

A recent study [81] examined the impact of PV penetration in the UK, where utility source series impedances are typically higher than in the U.S. It examined the probability distributions of voltages in a simulated 11 kV distribution system with varying levels of PV penetration, using an unbalanced load flow model. PV output was simulated using measured data with 1-min resolution. The probability density functions indicated that PV causes the distribution to shift toward higher voltages, but only by a small amount. Mean point of common coupling voltages increased by less than 2 V (on a 230-V nominal base).

The study's findings include the following: If one employs very strict reading of the applicable standard in the UK (BS EN 50160), then PV penetration is limited to approximately 33% by voltage rise issues. However, at 50% penetration, the voltage rise above the allowed limits was small, and so the authors suggest that the 33% limit is somewhat arbitrary. Reverse power flows at the sub-transmission-to-distribution substation did not occur even at 50% PV penetration.

Contrary to the results in [79], the authors of [81] found that at 50% penetration distribution system losses were reduced below the base-case values, largely because of reductions in transformer loading. Voltage dips due to cloud transients might be an issue at 50% penetration, and the authors suggest further study of this issue. The maximum PV penetration levels suggested in different literatures are summarized in Table 4.

6. Grid-connected inverters—control types and harmonic performance

Inverter technology is the key technology to have reliable and safety grid interconnection operation of PV system. It is also required to generate high quality power to ac utility system with reasonable cost. To meet with these requirements, up to date technologies of power electronics are applied for PV inverters. By means of high frequency switching of semiconductor devices with pulse width modulation (PWM) technologies, high efficiency conversion with high power factor and low harmonic distortion power can be generated. The microprocessor based control circuit

Table 5
A brief summary for various types of inverters.

Inverter type	Specifications
Line commutated	It uses a switching device like a commutating thyristor that can control the turn-on time while it cannot control the turn-off time by itself. Turn-off should be performed by reducing circuit current to zero with the help of supplemental circuit or source.
Self-commutated	It uses a switching device that can freely control the on-state and the off-state, such as IGBT and MOSFET. It can freely control the voltage and current (voltage and current type inverter) waveform at the ac side, and adjust the power factor and suppress the harmonic current, and is highly resistant to utility system disturbance. Most inverters for distributed power sources such as PV power generation now employ a self-commutated inverter [1]. *Voltage type*: It is a system in which the dc side is a voltage source and the voltage waveform of the constant amplitude and variable width can be obtained at the ac side. It is employed in PV power generation. It can be operated as both the voltage source and the current source when viewed from the ac side, only by changing the control scheme of the inverter. It produces a sinusoidal voltage output. It is capable of standalone operation supplying a local load. If non-linear loads are connected within the rating of the inverter, the inverter's output voltage remains sinusoidal and the inverter supplies non-sinusoidal current as demanded by the load. If the voltage or phase of the inverter is not identical to the grid, a theoretically infinite current would flow. This type of inverter is therefore connected to the grid via an inductance. The inverter voltage may be controlled in magnitude and phase with respect to the grid voltage (Fig. 9a and b). The inverter voltage may be controlled by controlling the modulation index and this controls the VARs. The phase angle of the inverter may be controlled with respect to the grid and this controls the power. *Current type*: It is a system in which the dc side is the current source and the current waveform of the constant amplitude and variable width can be obtained at the ac side. It produces a sinusoidal current output. It is only used for injection into the grid, not for stand-alone applications. The output is generated by producing a sinusoidal reference which is phase locked to the grid (Fig. 10). The output stage is switched so that the output current follows the reference waveform. The reference waveform may be varied in amplitude and phase with respect to the grid and the output current of the inverter follows the reference. The output current waveform is ideally not influenced by the grid voltage waveform quality. It always produces a sinusoidal output current. The current control inverter is inherently current-limited because the output current is tightly controlled even if the output is short circuited.

accomplishes PV system output power control. The control circuit also has protective functions, which provide safety grid interconnection of PV systems. Reduction of inverter system cost has been accomplished. There are various types of inverters as shown in Fig. 8 and a brief summary is presented in Table 5.

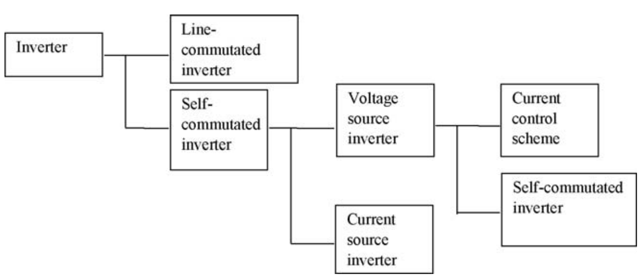

Fig. 8. Classification of inverter type.

6.1. Harmonics

It is important that any inverter system connected to the grid does not in any significant way degrade the quality of supply at the point of connection. It is also important to consider the effects of a poor quality of supply on an inverter added to the system. The harmonic content of most modern pulse with modulated sine wave inverters is typically less than 3% THD. This is better than the grid supply in many areas because of the many electronic loads connected to the grid which has simple rectifier front ends (Fig. 11).

These inverter systems should not seriously degrade the quality of supply with regard to harmonics. There is a large difference, however, between voltage control and current control inverters with respect to their harmonic affects on the grid.

Table 6 shows the difference between the voltage and current control schemes. In a case of the isolated power source without any

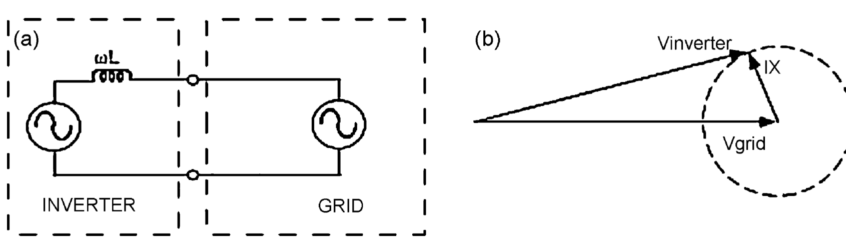

Fig. 9. (a) Voltage control inverter ideal equivalent circuit. (b) Voltage control inverter victor diagram.

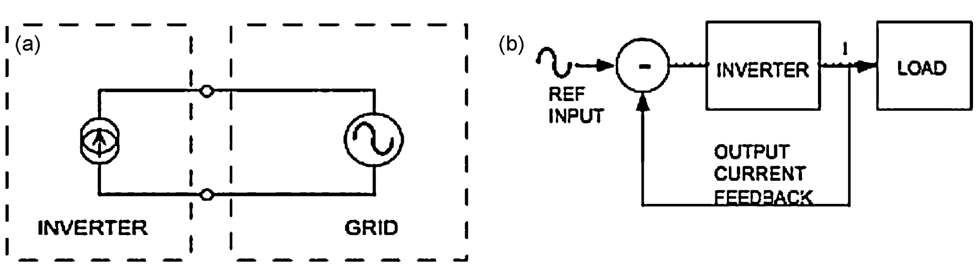

Fig. 10. (a) Current control inverter ideal equivalent circuit. (b) Current control inverter control system diagram.

Table 6
Difference between the voltage control and the current control schemes inverter.

	Voltage control scheme	Current control scheme
Inverter main circuit	Self-commutated voltage source inverter (dc voltage source)	
Control objective	ac voltage	ac current
Fault short circuit current	High	Low (Limited to rated current)
Stand-alone operation	Possible	Not possible

grid interconnection, voltage control scheme should be provided. Fig. 12 shows the configuration example of the control circuit of the voltage-type current-control scheme inverter.

The results of the survey show that the self-commutated voltage type inverter is employed in all inverters with a capacity of 1 kW or under, and up to 100 kW. The current control scheme is employed more popularly because a high power factor can be obtained with simple control circuits, and transient current suppression is possible when disturbances such as voltage changes occurs in the utility power system (Fig. 13). In the current control scheme, operation as an isolated power source is difficult but there are no problems with grid interconnection operation.

6.2. Inverters' operational analysis

The parameter generally used to evaluate the functioning of the inverter close to the MPP is the MPPT efficiency, ηMPPT. This parameter can be defined as the ratio between the energy obtained by the inverter of a given PV generator, and the energy that could be obtained of the same generator, if the inverter was provided with a MPPT ideal system [68]. The difficulty to evaluate this parameter may be due to its dependence of internal factors of the inverter (the MPPT's algorithm) and the external factors, such as PV generator, irradiance and temperature [82–84]. By known the irradiance ($H_{(t,\beta)}$) and cell's temperature (T_c) it is possible to calculated dc power of each generators in the MPP using the Eq. (15) [68]:

$$P_{\mathrm{mp}} = P^0_{\mathrm{FV}} x \frac{H_{(t,\beta)}}{G_{\mathrm{STC}}} x [1 - \lambda_{\mathrm{mp}} x (T_c - T_{\mathrm{ref}}) \quad (15)$$

Experimental data, can verify that the inverters work, in almost the totality of time, with MPPT's efficiency between 70 and 98%. The existing differences, performance better in the morning than in the afternoon, can be associated to the fact that the dc power of the inverter depends on its MPPT, which depends on the inverter temperature and the PV generator configuration in terms of operating voltage and current. Thus, the differences in the values obtained for MPPT's efficiency, can be associated to the inverter's temperature differences between morning, when the equipment is colder, and the afternoon when it is hotter.

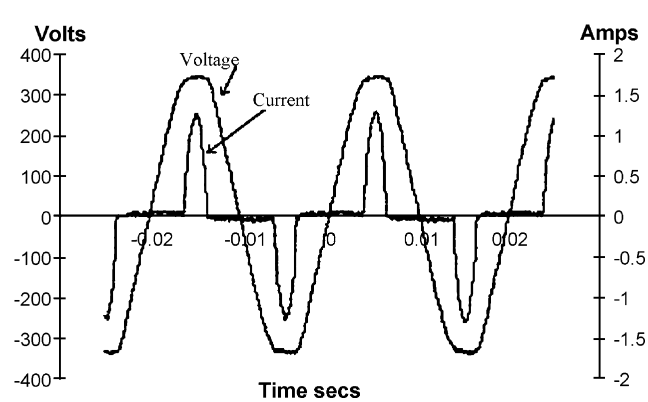

Fig. 11. Computer input current (rectifier front end).

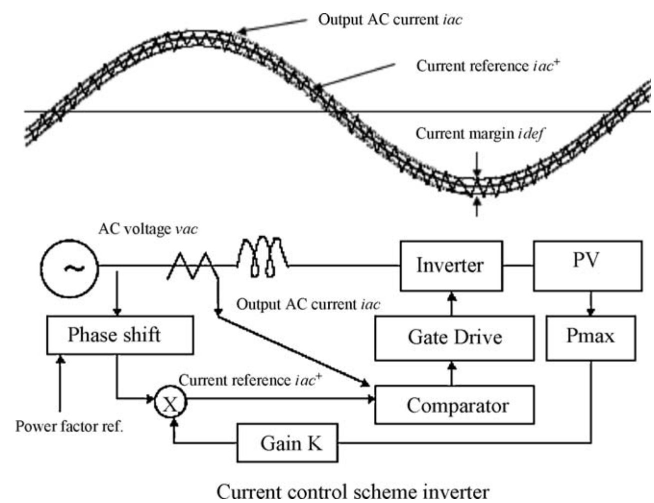

Fig. 12. Configuration example of the control circuit of voltage-type current-control scheme inverter [1].

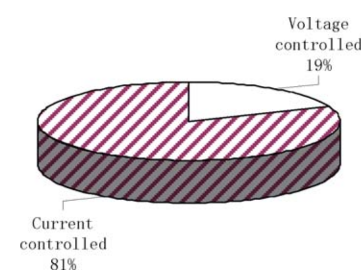

Fig. 13. Ratio of current controlled scheme and voltage controlled scheme inverters.

It should be emphasized that the daily average efficiencies found, ηMPPT, vary between 90 and 93% in days of clear sky, depending on the configuration. On the other hand, in cloudy days those values can fall to 5% or less, depending on the profile of the irradiance along the day [68].

7. Islanding detection methods

Islanding detection methods may be divided into four categories: passive inverter-resident methods, active inverter-resident methods, active methods not resident in the inverter, and the use of communications between the utility and PV inverter [85].

i. Passive inverter-resident methods rely on the detection of an abnormality in the voltage at the point of common coupling (PCC) between the PV inverter and the utility.
ii. Active inverter-resident methods use a variety of methods to attempt to cause an abnormal condition in the PCC voltage that can be detected to prevent islanding.
iii. Active methods not resident in the inverter also actively attempt to create an abnormal PCC voltage when the utility is disconnected, but the action is taken on the utility side of the PCC. Communication-based methods involve a transmission of data between the inverter or system and utility systems, and the data is used by the PV system to determine when to cease or continue operation.
iv. Passive methods not resident in the inverter such as utility-grade protection hardware for over/under frequency and over/under voltage protection relaying is the utility fall-back to assure loads are not damaged by out of specification voltage or frequency and may be required for very large PV installations.

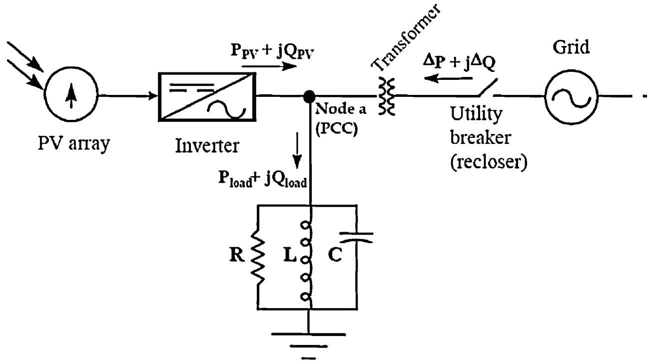

Fig. 14. PV system/utility feeder configuration [85,86].

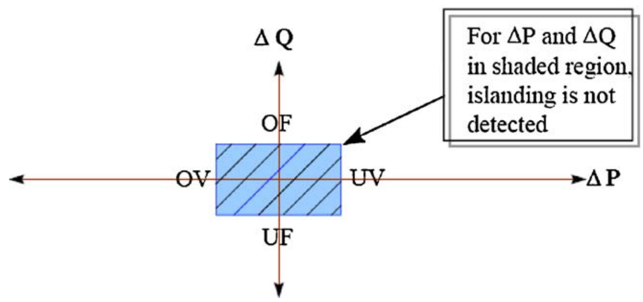

Fig. 15. Mapping of the NDZ in ΔP vs. ΔQ space for over/under voltage and over/under frequency.

All grid-connected PV inverters are required to have over/under frequency protection methods (OFP/UFP) and over/under voltage protection methods (OVP/UVP) that cause the PV inverter to stop supplying power to the utility grid if the frequency or amplitude of the voltage at the PCC between the customer and the utility strays outside of prescribed limits [85]. These protection methods protect consumer's equipment but also serve as anti-islanding detection methods. Consider the configuration shown in Fig. 14, in which power flows and node "a" have been labeled. Node "a" is the PCC between the utility and PV inverter. When the recloser is closed and the utility is connected, real and reactive power $P_{PV} + jQ_{PV}$ flows from the PV inverter to node "a", and power $P_{load} + jQ_{load}$ flows from node "a" to the load. Summing power flows at node "a":

$$\begin{aligned}\Delta P &= P_{load} - P_{PV}\\ \Delta Q &= Q_{load} - Q_{PV}\end{aligned} \tag{16}$$

are the real and reactive power flowing into node "a" from the utility. If the PV inverter operates with a unity power factor (that is, the PV inverter output current is in phase with the voltage at node "a"), then $Q_{PV} = 0$ and $\Delta Q = Q_{load}$.

The literature suggests that the probability of ΔP and ΔQ falling into the non-detection zone (NDZ) of the OVP/UVP and OFP/UFP can, in some cases, be significant [87–89]. Because of this concern, the standard over/under voltage and frequency protective devices alone is generally considered to be insufficient anti-islanding protection. A mapping of the NDZ of the four standard over/under voltage and frequency protection methods in the RLC load space and the ΔP–ΔQ space can be found in the literature [90,91].

The NDZ of the over/under frequency protective devices includes all L and C combinations falling in the cross-hatched area in Fig. 15 shows the same NDZ for changes of voltage and frequency. Phase jump detection (PJD) involves monitoring the phase difference between the inverter's terminal voltage and its output current for a sudden "jump" [92,93]. Under normal

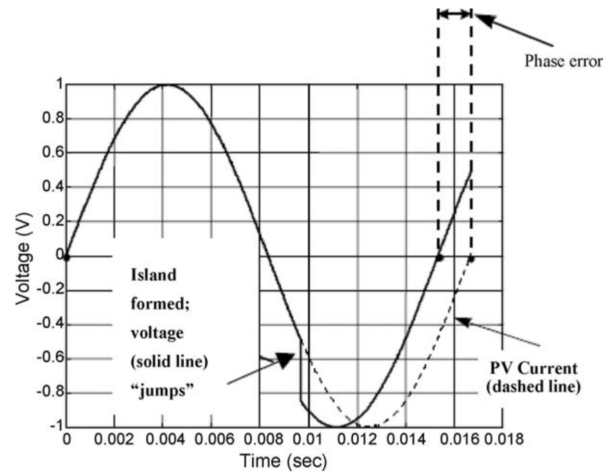

Fig. 16. Diagram showing the operation of the phase jump detection method.

operation and for current-source inverters, the inverter's output current waveform will be synchronized to the utility voltage by detecting the rising (or falling) zero crossings of v_a at node "a" in Fig. 15. Fig. 16 shows the operation of the phase jump detection method.

Detection of voltage harmonics and detection of harmonics: In this method, the PV inverter monitors the THD of the node "a" voltage v_a and shuts down if this THD exceeds some threshold. Under normal operation, the utility, being a "stiff" voltage source, forces a low-distortion sinusoidal voltage (THD ≈ 0) across the load terminals, causing the (linear) load to draw an undistorted sinusoidal current. Summing at node "a" when the utility is connected the harmonic currents produced by the inverter will flow out into the low impedance grid. Because these harmonic currents are kept small and the impedance of the utility is generally low, these harmonic currents interact with the very small utility impedance to produce only a very small amount of distortion in the node "a" voltage. Typically, when the inverter is connected to the utility grid, the THD of the voltage v_a is below the detection point.

A typical requirement for a grid-connected PV inverter is that it produce no more than 5% THD of its full rated current [94,95].

Multiple methods for detection of an island are used in the ENS (MSD). They are an impedance change detection method with additional over/under voltage and frequency trips. Each of these independent units continuously monitors the connected grid by monitoring voltage, frequency and impedance. The redundant design, as well as an automatic self-test before each connection to the grid, provides an improvement in the reliability of the method. The different designs being used by manufacturers today vary according to when the design was implemented relative to the evolutionary improvements that have taken place. All units monitor the utility voltage, frequency and impedance. The general block diagram as outlined in German standard DIN VDE 0126 is shown in Fig. 17 [96].

The phase criteria for several common islanding prevention schemes, along with the methods for using them, are given in Table 7. The methods considered are OFR/UFR, PJD, SMS, AFD, and SFS. The details of the islanding prevention methods are given elsewhere [91,97]; however, the reader should be aware that all of these methods rely on a change in the frequency of the voltage at node to detect islanding.

In the table, ω is the frequency of the voltage at node "a" and ω_o is the utility voltage frequency. Several design parameters also appear in the table: φ_{th} is the phase threshold used in PJD (commonly between 2 and 5 [91]), $G(j\omega)$ is the transfer function

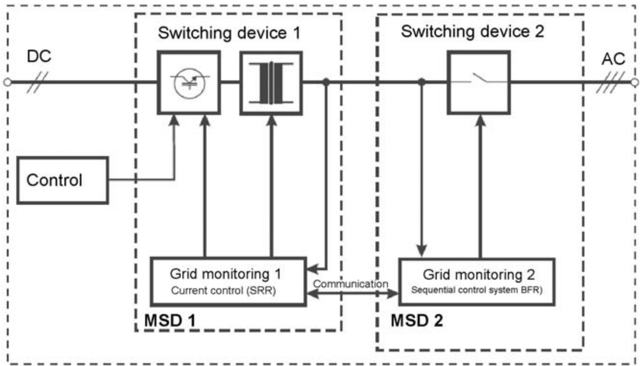

Fig. 17. Design of an automatic disconnection device according to DIN-VDE-0126.

that implements the SMS method, cf is the "chopping fraction" used in the AFD method, K is a gain used in SFS, and $\Delta\omega$ is defined as $\omega - \omega_o$.

8. Performance and reliability of inverter hardware

Performance and reliability of inverters, and most other power electronics, in PV systems has been perceived by many to be poor over the past 20 years. The word 'perceived' is used here because many other factors have contributed to reported failures other than simply inverter problems. Utility-interactive PV inverter islanding or problems may occur as a result of the following conditions [42,85]:

i. A fault that is detected by the utility, and which results in opening a disconnecting device, but which is not detected by the PV inverter or protection devices.
ii. Accidental opening of the normal utility supply by equipment failure.
iii. Utility switching of the distribution system and loads.
iv. Intentional disconnect for servicing either at a point on the utility or at the service entrance.
v. Excessive utility transients or high utility voltage.
vi. Inverters installed in untested and improper environments.
vii. Improper trip set points for either dc or ac conditions.
viii. Improper inverter installation.
ix. Ground fault detectors for the array set at excessively low current levels.
x. Poor system design, including improper fusing, improper grounding, improper sensor locations, improper wiring and incorrect array specifications.
xi. System voltages those were different than inverter operating specifications.
xii. Human error or malicious mischief.
xiii. An act of nature.

Table 8
Characteristic parameters and self-consumption [68].

V_{DC} (V)	K_0 (%)	K_1 (%)	K_2 (%)	P_{self} (W)
150	1.1	0.4	6.4	11
250	1.3	2.4	4.8	13
330	1.5	4.3	3.6	15

Despite being electrical equipment of high performance in dc/ac conversion, they never reach 100% efficiency [98]. They reach their optimum performance in the range of 85–96% efficiency for power values close to the nominal rating, while for the generation of small amounts of power-in conditions of cloudiness, start-ups, sunrise and sunset—the efficiency can diminish considerably. The monitoring of the point of maximum power and the adaptation to the variable conditions of generation involves a small loss of power during normal operation conditions. For single-phase inverters, the sum of all the losses can be about 8–20% of the total energy generated, depending on the quality of the equipment. The data provided by the manufacturers for each model can be included in the database of the computer application; also the loss factor by monitoring the MPP and the start-up/shutdown of the inverters should be considered [53].

The power losses in the inverter can be interpreted by the sum of three components, which are: the self-consumption losses, P_{self} (W); the lineal losses with the electric current (voltage drops in the semiconductors, etc.), $K_1 P_{out}$; and the losses proportional to the squared electric current (resistive losses, etc.), $K_2 (P_{out})^2$ (Martin, 1998 – cited by [68]).

Thus, the losses in Watts are given by the following equation:

$$P_{losses} = P_{self} + K_1 P_{out} + K_2 (P_{out})^2 \tag{17}$$

Normalizing Eq. (17) by the rated power of the inverter (P^0_{Inv}), making the $p_{out} = P_{out}/P^0_{Inv}$ and considering $k_0 = P_{self}/P^0_{Inv}$, $k_1 = K_1$ and $k_2 = K_2 P^0_{Inv}$, the following Eq. (18) can be obtained:

$$P_{losses} = K_0 + K_1 P_{out} + K_2 (P_{out})^2 \tag{18}$$

The great advantage of this equation is that it makes possible to characterize the behavior of the losses in the inverter and, consequently, its energy efficiency, based on only three non-dimensional parameters, k_0, k_1, and k_2, which can be obtained experimentally, such as the ones displayed in Table 8. The characteristic parameters and the average annual energy efficiency of the inverter, η_{Inv}, are shown associated to each one of the groups experimentally analyzed. Those values also reflect the features of each configuration in terms of input voltage and installed W_p.

9. The overall conclusion and recommendation

- The tendency of over-sizing excessively the PV generator in relation to the inverter still exists, and this procedure can affect

Table 7
Phase criteria for several islanding prevention methods (from [91,97]).

Islanding prevention scheme	Phase criterion	How to use phase criterion (P.C)
OFR/UFR	$\tan^{-1}\left[R\left(\omega C - \frac{1}{\varpi L}\right)\right] = 0$ $\Downarrow$ $\omega C - \frac{1}{\varpi L} = 0$	If ω at which the P.C. is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ
PJD	$\tan^{-1}\left[R(\omega_0 C - \frac{1}{\varpi L})\right] \le \phi_{th}$	If the P.C. is satisfied at ω_0 (line frequency), the RLC load is inside the NDZ
SMS	$\tan^{-1}\left[R(\omega C - \frac{1}{\varpi L})\right] = -\arg[G(j\omega)]$	If ω at which the P.C. is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ
AFD	$\tan^{-1}\left[R(\omega C - \frac{1}{\varpi L})\right] = -\frac{\pi c f}{2}$	If ω at which the P.C. is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ
SFS	$\tan^{-1}\left[R(\omega C - \frac{1}{\varpi L})\right] = -\frac{\pi(c f_{k-1} + K\Delta\omega)}{2}$	If ω at which the P.C. is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ

the inverter's operational lifetime. The maximum PV power in a power network for which balanced conditions never occur is approximately two to three times the minimum night load of the relevant power network.

- Balanced conditions occur very rarely for low, medium and high penetration levels of PV systems. The probability that balanced conditions are present in the power network and that the power network is disconnected at that exact time is virtually zero. Islanding is therefore not a technical barrier for the large-scale deployment of PV system in residential areas.
- The penetration level of PV systems does not significantly influence how often and for how long balanced conditions between the load and the PV systems occurs. Balanced conditions between active and reactive load and the power generated by the PV systems do occur very rarely for low, medium and even high penetration levels of PV systems.
- The probability of a balanced condition does not depend on the number of houses connected to a feeder. The probability of encountering an island is virtually zero.
- It was found that failure in inverter is the most frequent incidents. This is mostly caused by the lack of experience in first production stage and newly designed inverters have good reliability. Some unexplained inverter failure might be caused by disturbance from grid, reclosing, and other interconnecting issues.
- Distributed generation is an emerging technology that has the potential to offer improvements in power system efficiency, reliability and diversity, and to help contribute to making renewable a greater percentage of the generation mix. While a great amount of knowledge has been gained through past experience, the practical implementation of distributed generation (DG) has proved to be more challenging than perhaps originally anticipated.
- Passive methods for detecting an islanding condition basically monitor selected parameters such as voltage and frequency and/or their characteristics and cause the inverter to cease converting power when there is sufficient transition from normal specified conditions. Active methods for detecting the island introduce deliberate changes or disturbances to the connected circuit and then monitor the response to determine if the utility grid, with its stable frequency, voltage and impedance, is still connected. If the small perturbation is able to affect the parameters of the load connection within prescribed requirements, the active circuit causes the inverter to cease power conversion.
- The effects on harmonics in case of multiple PV systems operation need further investigation.
- The utilization of $P^0_{\mathrm{Inv}}/P^0_{\mathrm{PV}}$ values between 60 and 100% should be recommended, depending on the location, type of installation and on the equipment kind.
- It is strongly recommended that PV inverters are operated at unity power factor. It is not advised to use PV inverters with a variable power factor as this, at high penetration levels, may increase the number of balanced conditions and subsequently increase the probability of islanding.
- Research and develop regulation concepts to be embedded in inverters, controllers, and dedicated voltage conditioner technologies that integrate with power system voltage regulation, providing fast voltage regulation to mitigate flicker and faster voltage fluctuations caused by local PV fluctuations.
- Investigate dc power distribution architectures as an into-the-future method to improve overall reliability (especially with microgrids), power quality, local system cost, and very high penetration PV distributed generation.
- Develop advanced communications and control concepts that are integrated with solar energy grid integration systems. These are the key to providing very sophisticated microgrid operation that maximizes efficiency, power quality, and reliability.
- Identify inverter-tied storage systems that will integrate with distributed PV generation to allow intentional islanding (microgrids) and system optimization functions (ancillary services) to increase the economic competitiveness of distributed generation.

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